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# Integrated production of sugarcane ethanol and soybean biodiesel: Environmental and economic implications of fossil diesel displacement

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ABSTRACT

The sugarcane industry in Brazil has been considered promising for the production of advanced fuels and bio-based products. However, the sugarcane crop requires high volumes of fossil fuel for cultivation and transport. The use of biodiesel as a diesel substitute could reduce the environmental burdens associated with this high consumption. This work performed a stochastic evaluation of the environmental and economic implications of the integrated production of sugarcane bioethanol and soybean biodiesel, in comparison with the traditional sugarcane-to-ethanol process. The analysis was focused on the states of Goiás, Mato Grosso and São Paulo, where this integration would be particularly attractive. The environmental aspects addressed were the fossil energy use and the GHG emissions in a cradle-to-gate approach. The economic analysis comprised the evaluation of the net present value of an incremental cash flow generated by the soybean production and by the adjacent plants of oil extraction and biodiesel. Results indicate that the integrated system is likely to improve the ethanol environmental performance, especially with regard to the fossil energy use. The integration is economically feasible but highly uncertain; however, it could be significantly improved through fiscal incentives to biodiesel producers, founded on the reduction of fossil energy use and on improvements in logistics. In addition, the proposed model may also assist in the design of other integrated systems applied to the sugarcane sector in Brazil.



## 1. Introduction

Integrated complexes, also called biorefineries, have been proposed as an alternative to improve the interaction of bioenergy, chemicals and food production by applying sustainable processing of biomass [1]. Biorefineries are able to produce a range of products from different raw materials and, additionally, may reduce the commitment of land for bioenergy production and provide diversification and optimization of agricultural systems [2]. Initial studies concerning the integrated production of food and bioenergy have demonstrated that this interaction can also provide the rural development due to the high renewability and energy sustainability [3], and afford better energy and environmental performance [4].

Due to the diversity of products (sugar, bioethanol, bioelectricity, etc.) and the possible applications for the residues, the sucroenergetic sector in Brazil is already an important model of biorefinery. However, there is still potential for improvement and different systems can be applied to the sector, such as integrated production of bioenergy and food [4], ethanol, methane and heat [5], ethanol and biodiesel [2], among others. Biorefinery models can also add value to the sector [6].

Despite the potential to produce many bioproducts, the sugarcane sector is characterized by the high diesel consumption, which is the main non-renewable energy input and one of the main sources of greenhouse gas (GHG) emissions in the ethanol life cycle. Further, considering an average specific consumption of 4 L/t sugarcane [7], it can be estimated that the sugarcane sector alone was responsible for about 4% of the total diesel consumption in Brazil in 2011.

Brazil is also known by its biodiesel program. Due to the soybean relevance in the Brazilian agribusiness as a result of a suitable development of agronomic, industrial and logistic aspects over decades, the soybean production chain met the Brazilian Biodiesel Program (PNPB) demand. Soybean has been leading as the main feedstock for biodiesel production, comprising about 80% of the biodiesel sources. Other feedstocks include beef tallow, cottonseed, waste frying oil, swine and chicken fat, palm oil, peanut and sunflower [8].

The high demand for diesel in sugarcane production and the relevance of soybean as feedstock for biodiesel production in Brazil

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have encouraged efforts toward the integration of these bioenergy systems. Such system has already been tested in Brazil, including the joint production of biodiesel, ethanol, sugar and electricity [9].

In this study, we investigated an integrated system in which a soybean biodiesel plant is integrated into the sugarcane sector, assuming that the replacement of fossil diesel by the locally produced renewable fuel would improve the environmental and economic performance of the traditional sugarcane biorefinery. The environmental aspects addressed in this study were the fossil energy use and the GHG emissions. The traditional ethanol production was used as the reference case for comparisons. The environmental and economic implications of the integrated system were assessed though a stochastic approach based on the Monte Carlo method.

## 2. Integrated system

In the proposed model, sugarcane and soybean oil are processed in a combined ethanol–biodiesel plant, which uses only bagasse as fuel. The distillery provides the utilities for the biodiesel plant. We assumed that oil is provided by the soybean grown in the sugarcane reforming areas, including the direct oil from the grain and the additional oil acquired from the sale of soybean meal (defined as Façon exchange [9]) (Fig. 1).

Based on the average conditions of the Brazilian south-central region (which mainly reflect the conditions of the São Paulo state), our previous study [10] showed that this integration would be able to considerably reduce the fossil energy use in the ethanol life cycle, but with minor implications for the GHG emissions. However, this integration would be particularly attractive under the conditions featured in the Midwest region (e.g., land availability, background in soybean cultivation, flat terrain and large scales). Therefore, in the present study we focused the analysis on the states of Goiás and Mato Grosso (Fig. 2), using representative data collected through site visits. Special attention was paid to the uncertainties of the model, which were evaluated through sensitivity analyses and the Monte Carlo (MC) simulation. Additionally, an economic analysis was performed to indicate the viability of this integration model.

The integration described in this study comprises the following assumptions:

- Soybean is produced in the sugarcane renovation area.
- The biodiesel plant includes the oil extraction unit.
- The soy meal is traded for additional oil.
- The soybean oil converted into biodiesel is provided by the soybean cultivated in the sugarcane renovation area and by the additional oil acquired from the soy meal exchange. No additional area was assumed.
- The soybean oil transesterification employs sugarcane ethanol (ethyl route).
- Diesel used for sugarcane production is partially replaced by biodiesel without engine modification [11]. No biodiesel surplus is produced.
- Vinasse (a liquid effluent from the distillation process) and filtercake (a coproduct from sugarcane juice filtration) are used for fertirrigation and organic fertilization, respectively. Filtercake is applied in 100% of the renovation area.
- Sugarcane bagasse is completely used for heat and power generation, meeting the energy requirements of the combined plant (ethanol and biodiesel) and producing electricity surplus.
- Fifty percent of the sugarcane area is irrigated (salvage irrigation).

Except for the states in the Northeast region, sugarcane is practically not irrigated in Brazil. When employed, irrigation is mostly used after the sugarcane planting to ensure sprouting ("salvage irrigation"). In the states of Mato Grosso and Goiás, sugarcane irrigation is still incipient, and the procedures and application rates vary within a wide range among the producers.

## 3. Methods

### 3.1. Life cycle assessment

A comparative analysis was performed between a traditional ethanol production system and a sugarcane–soybean integrated system applying the life cycle assessment (LCA) technique according to ISO 14040:2006 [12] and ISO 14044:2006 [13]. The functional unit was defined as 1 MJ of ethanol. The fossil energy use and the GHG emissions were evaluated in a cradle-to-gate approach, comprising the sugarcane cultivation up to ethanol processing. Fossil energy use is expressed by the ratio between the fossil energy invested to produce the biofuel, and the bioenergy produced. The results for life cycle GHG emissions are expressed in $CO_2e$ using the GWP100 given by IPCC as characterization factors [14].

The foreground information (Appendix A, Tables A1 and A2) was based on data collected from sugarcane mills, sugarcane and soybean suppliers, and biodiesel plants. The data were collected in the states of São Paulo, Mato Grosso and Goiás (Fig. 2), employing direct field observation methods through questionnaires. The field data were compared to the literature information, which supported the statistical parameters used in the sensitivity and

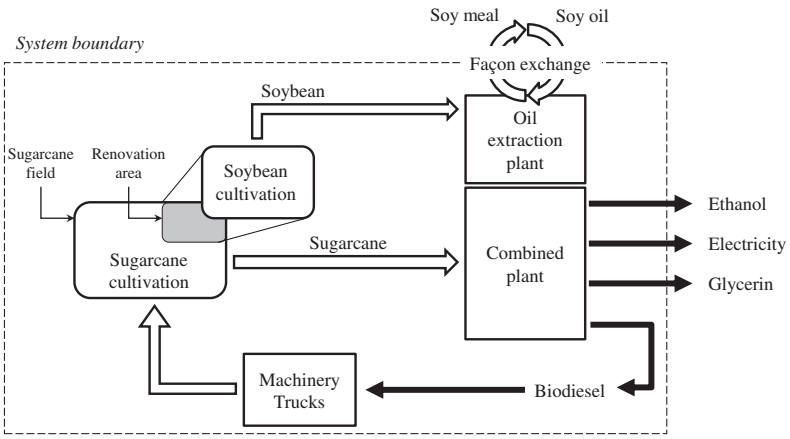


**Fig. 1.** Sugarcane–soybean integration design considered in this study.